Your next hour

- What is HRXCT?
- Applications and recent results
  - Petrographic observation
  - Pore space
  - Fabrics (lineations, foliations, preferred orientations)
  - Object measurements

High-Resolution X-ray Computed Tomography (HRXCT)

- Industrial equivalent of medical CAT scan
  - Creates X-ray image of “slice” through object
  - Consecutive slices can make 3D volume
- Same principles as medical, but…
  - Higher-energy, more focused X-rays
  - Smaller, higher-resolution detectors
  - More precise positioning
  - Longer acquisition

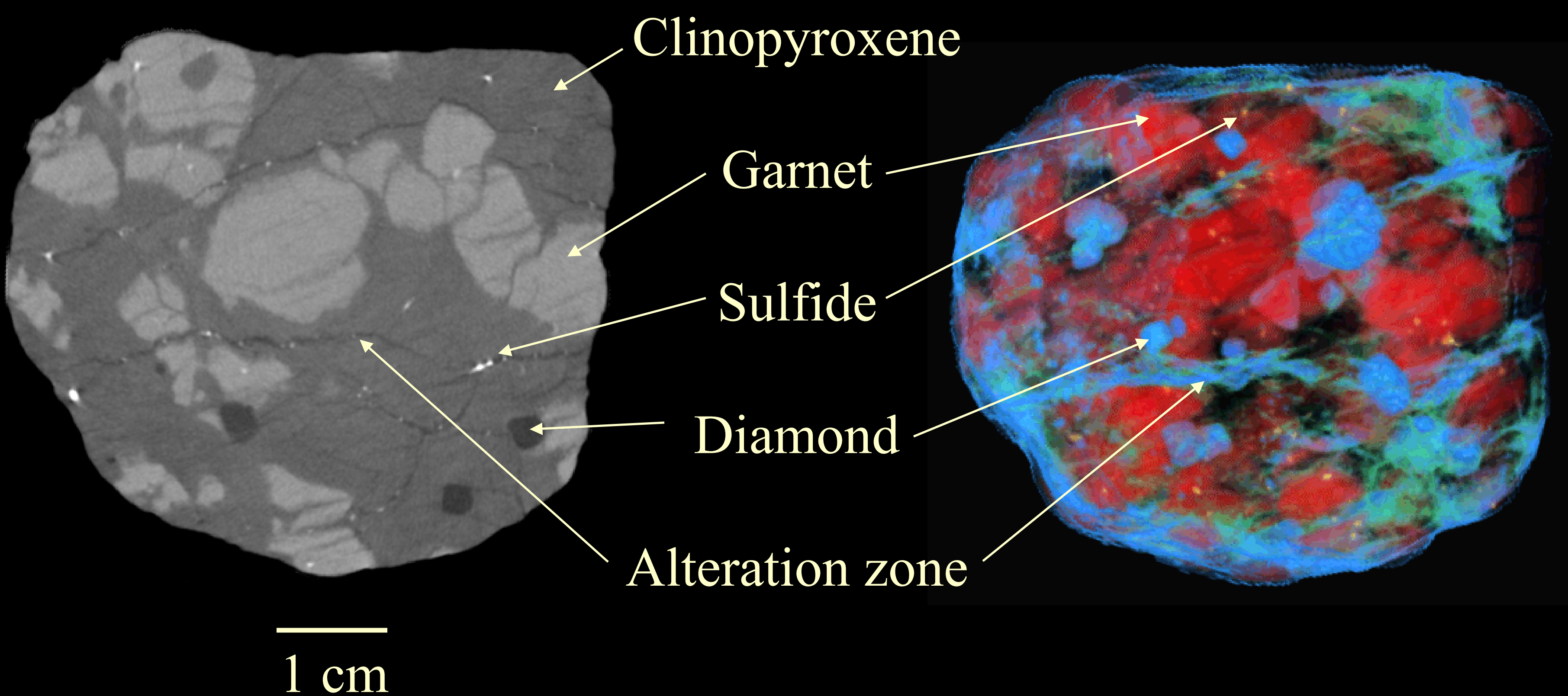
CT Imagery

- Images are slices through object
- Images are composed of voxels
  - “volume elements”; pixels with thickness
- Grayscales represent amount of X-ray attenuation that occurred in each voxel
  - Dependent on density, atomic number
    - Also X-ray energy spectrum, detector efficiency

Example: Diamondiferous Eclogite

Slice

3D Reconstruction

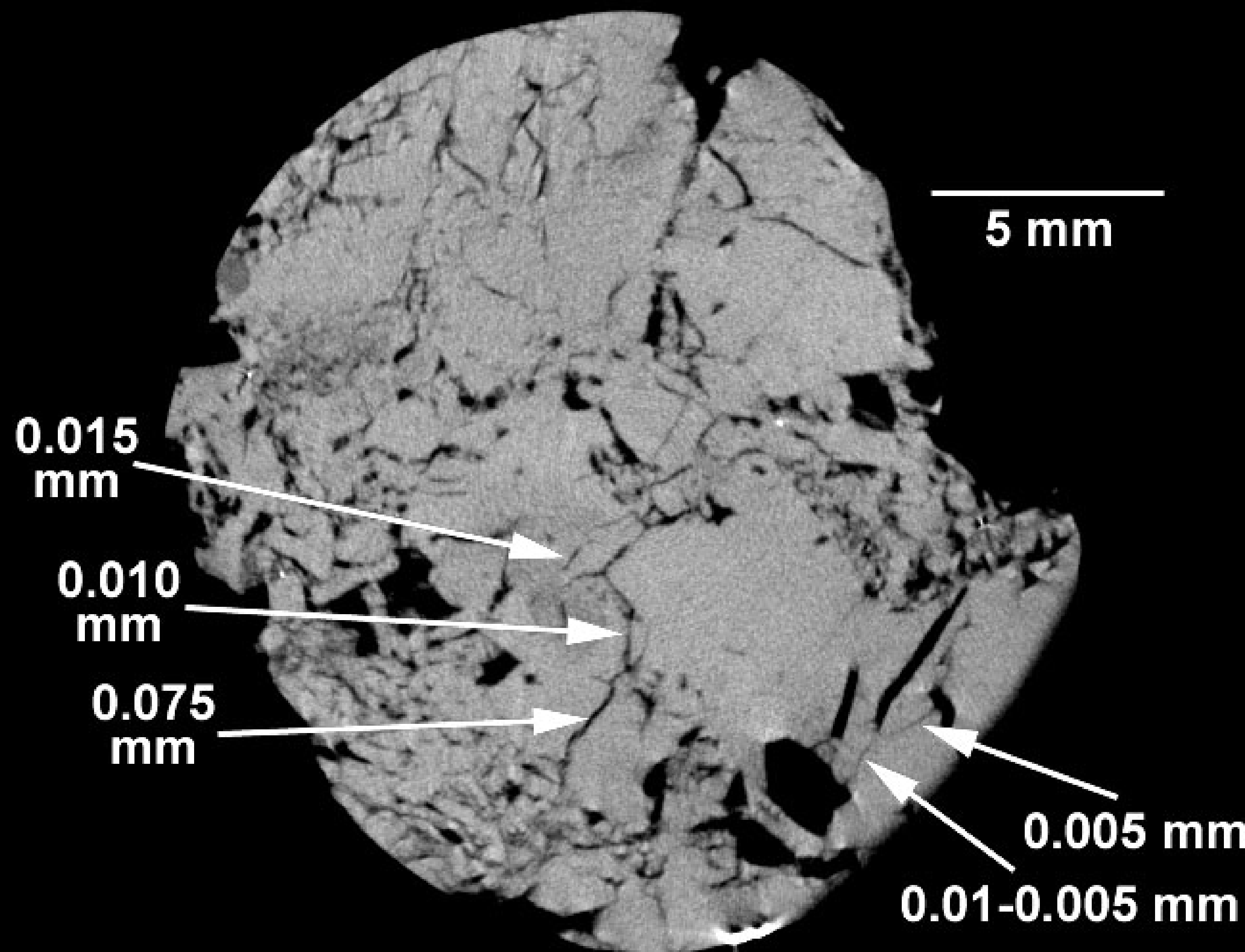


Sample courtesy of Larry Taylor, University of Tennessee

CT Image Resolution

- Mainly determined by pixel size
  - Images are 512x512 or 1024x1024
    - Justified by number of detectors, focal spot size
  - Entire object cross-section must be in scan field
  - Pixel size = field of view/number of pixels
- What is being resolved?
  - Objects must (generally) span several pixels
  - Cracks and boundaries can be distinguished at the sub-pixel level (down to ~0.1 pixel width)

Example: Fractured limestone



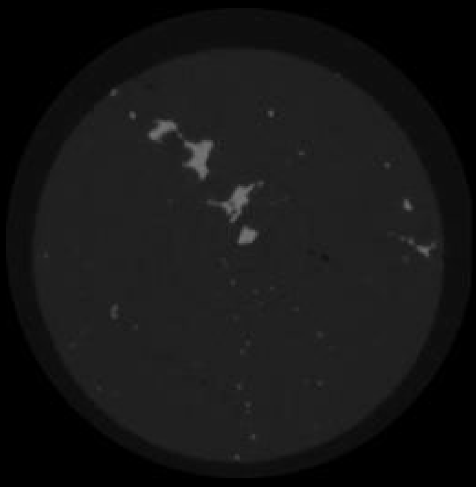
Thin section measurements by Brenda Kirkland

A Research Crossroads

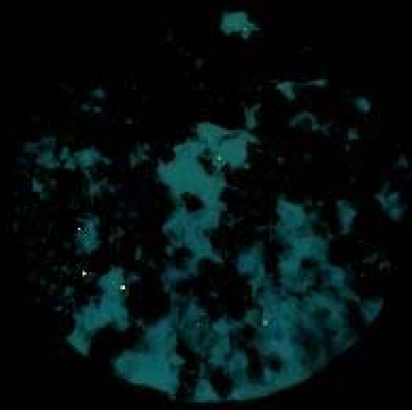
- Projects done in virtually all geologic disciplines
  - Petrology, paleontology, structural geology, hydrogeology, sedimentology, geophysics, planetary geology
- Also other fields
  - Anthropology, archaeology, biology, engineering, medicine

Petrographic observation

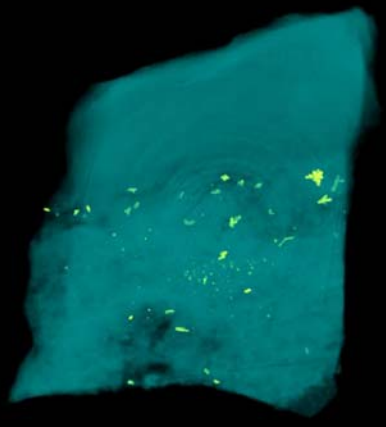
- 2D: Like having 1000 thin sections, in all orientations
- 3D: Volume rendering
- *In situ* observations of Au grains (R. Kyle, A. Mote)



5 mm



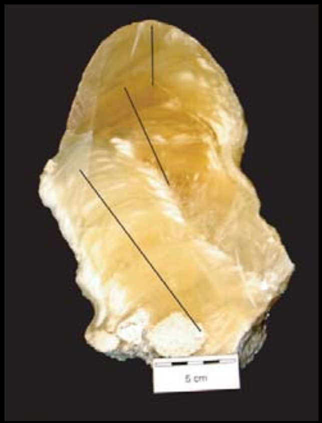
5 mm



5 cm

Mo' petrographic possibilities

- Thin section supplement: What's off-plane?
  - Scan before preparing a section
- "Look before you cut"
  - Find central sections, inclusions for chemical/isotopic analysis

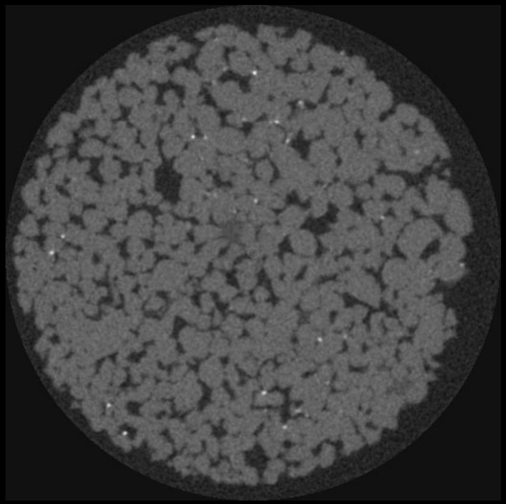


Speleothem

From: Mickler, Ketcham and Colbert, in prep.

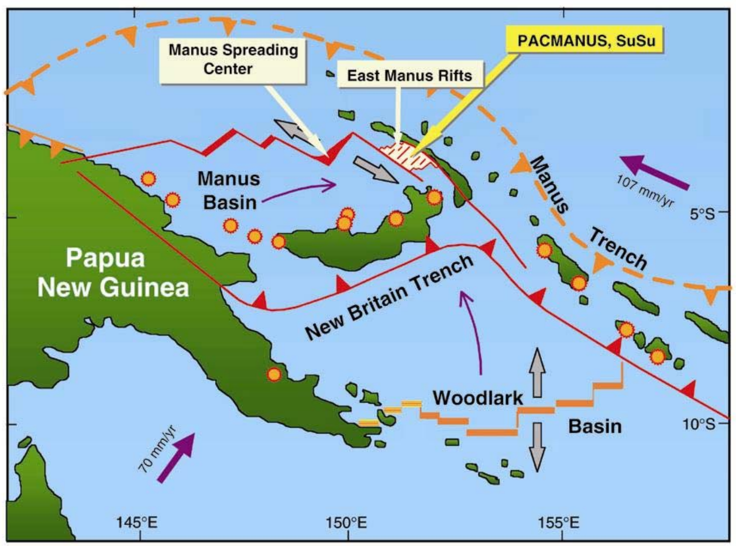
Analyzing Porosity

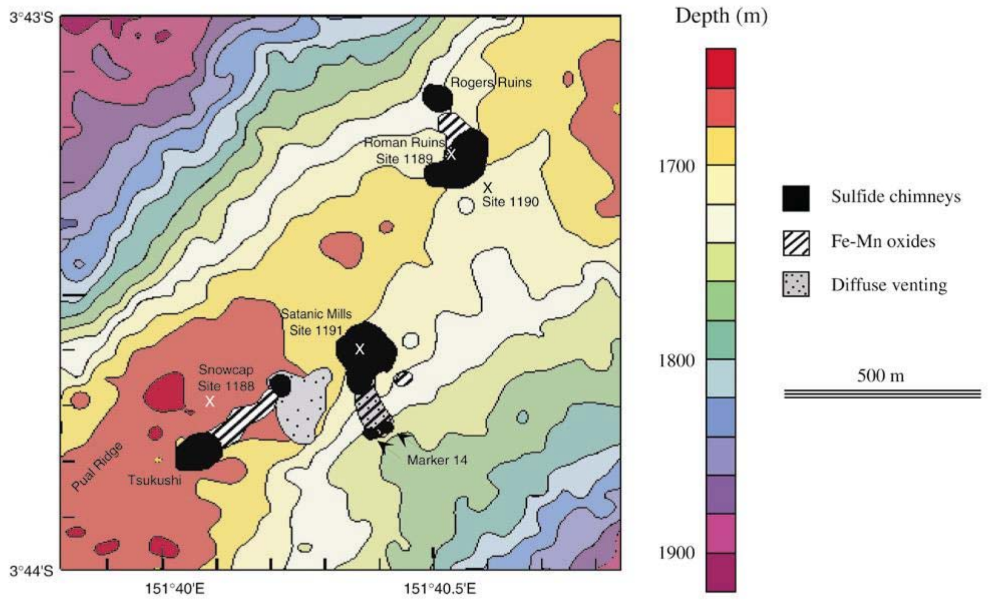
- Direct imaging
  - Resolution down to 5-10 μm
  - Only small samples (5-10 mm)
- Indirect imaging
  - Main principle: Partial Volume Effect
  - Scan sample twice: once dry, once saturated
  - Subtract images to see where water is
  - Resolution essentially unlimited



5 mm diameter

Porosity development in deep-sea hydrothermal system

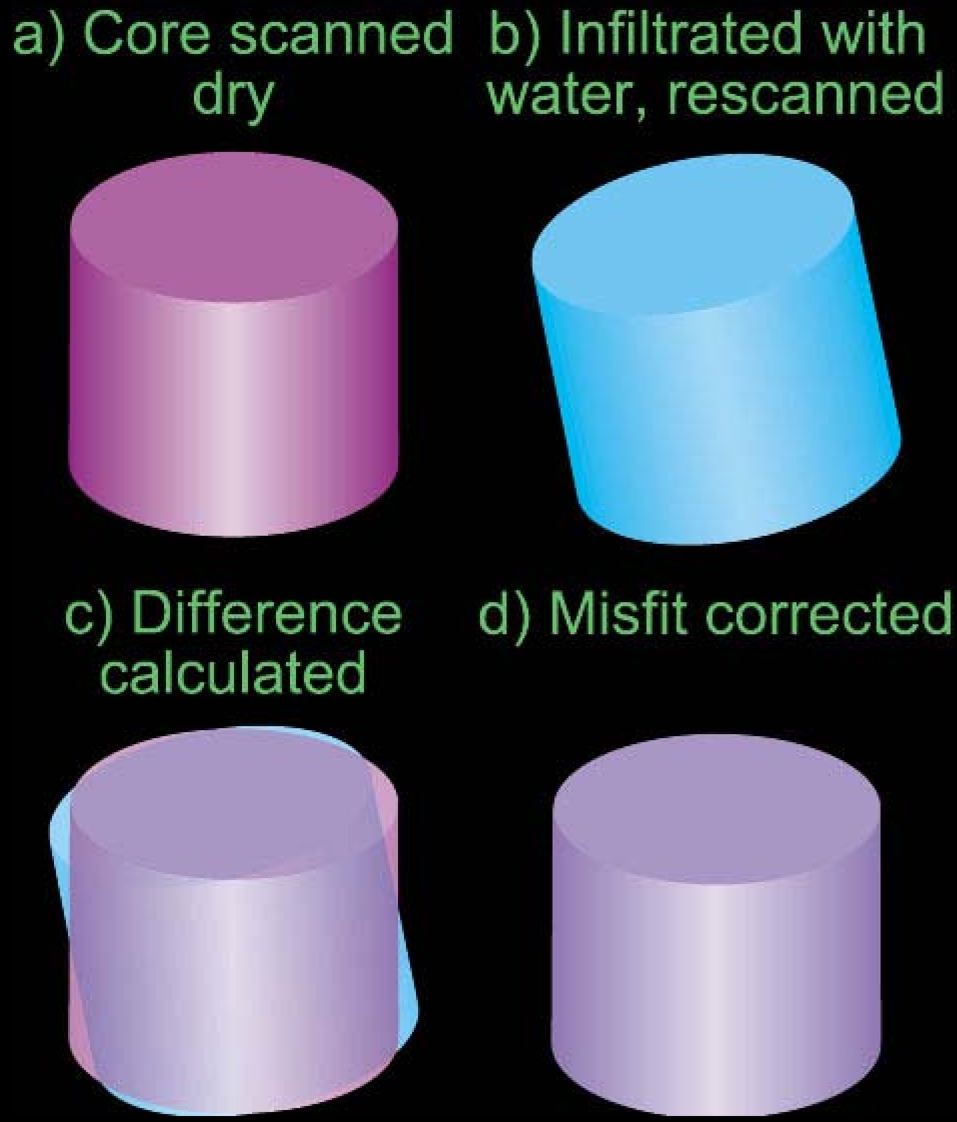




Study in collaboration with G. Iturrino, Lamont-Doherty Earth Observatory

Partial porosity measurement

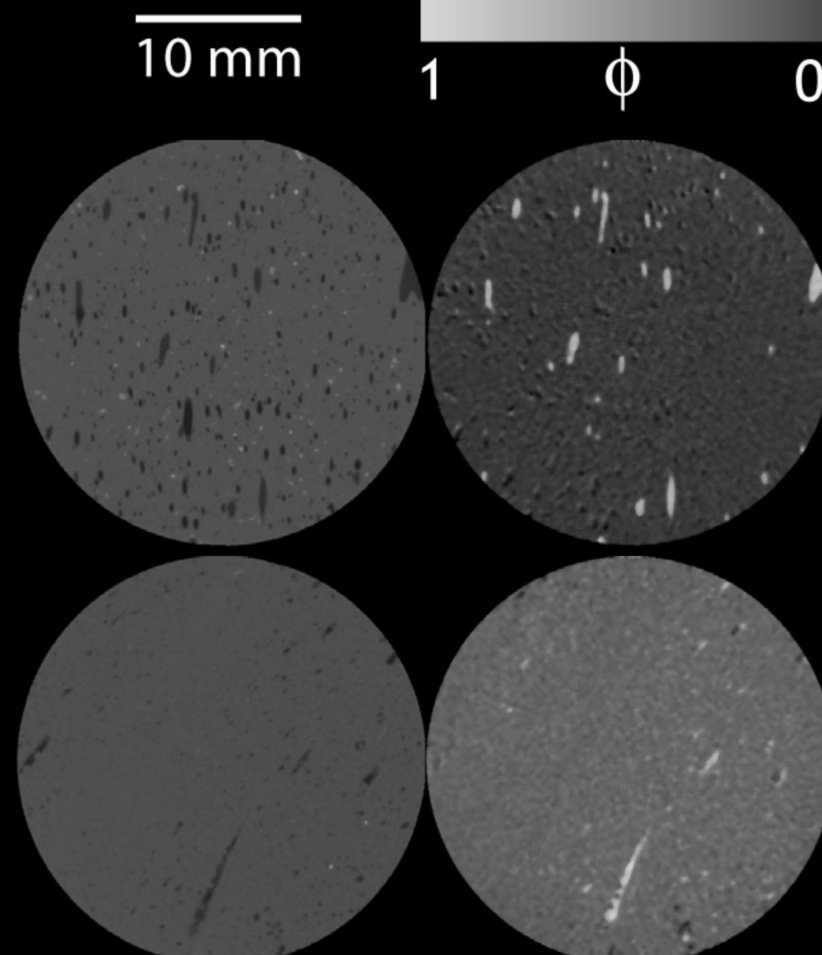
25-mm mini-cores



Incipient alteration

CT Image

Porosity Distribution



3R

11R

High alteration

CT Image

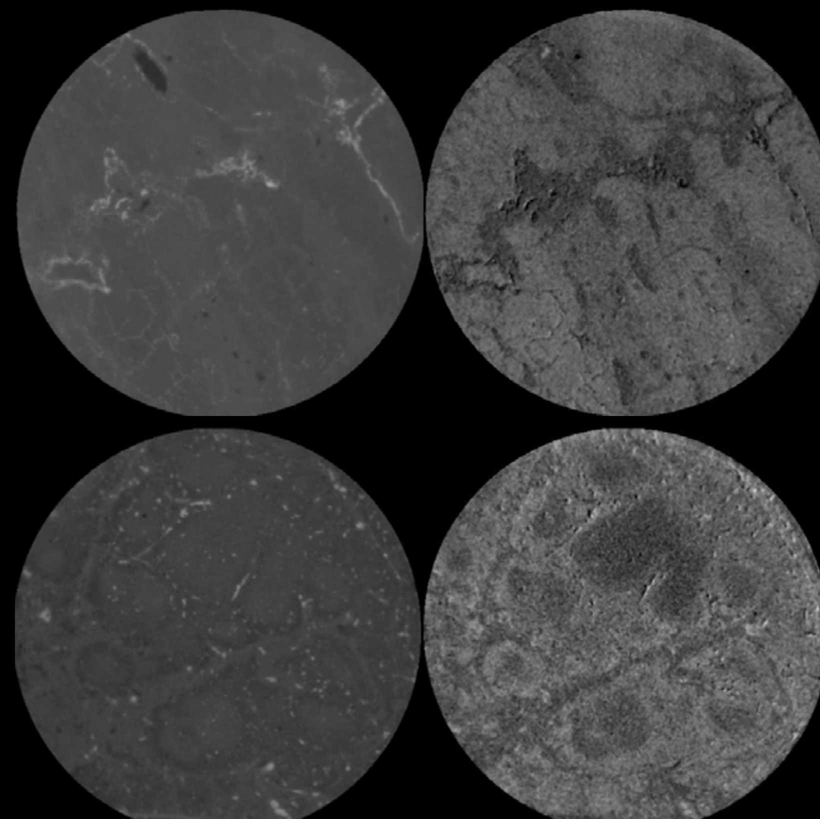
10 mm

Porosity Distribution

1 ϕ 0

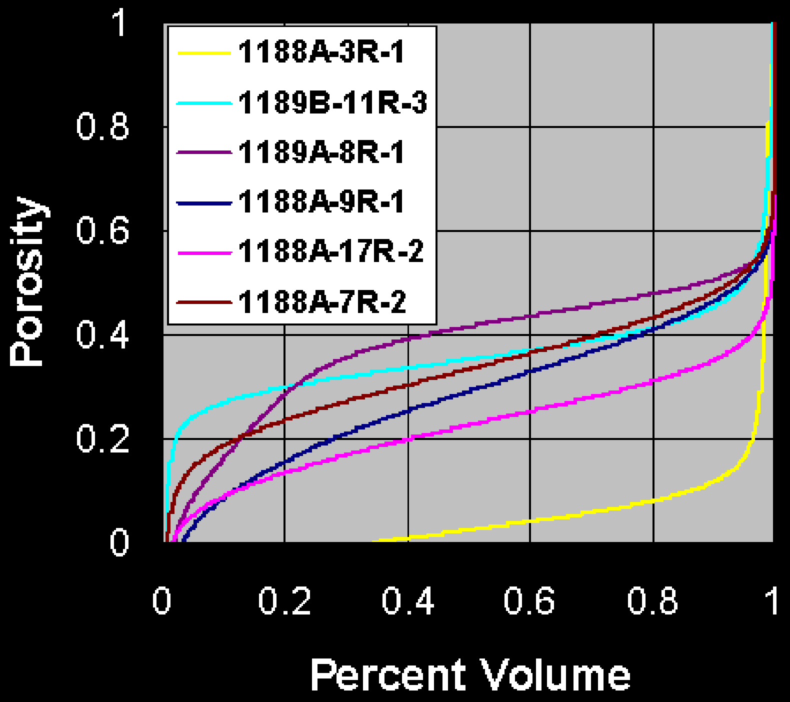
9R

17R

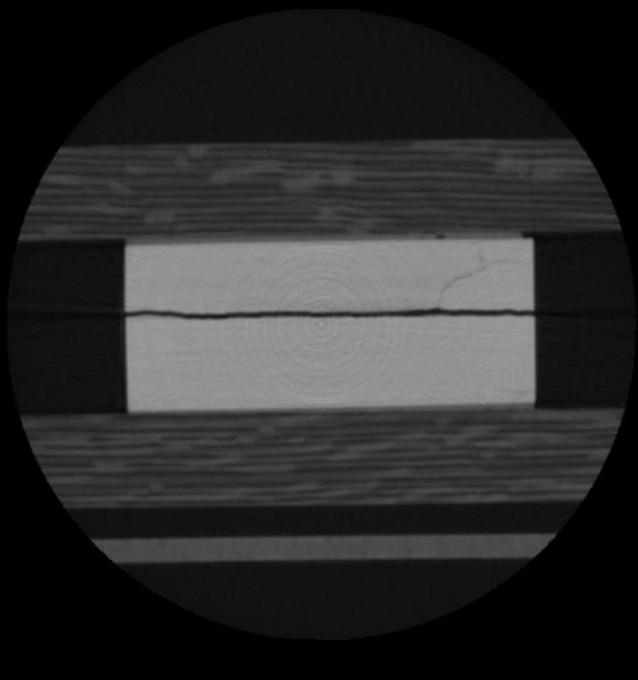


From porosity to permeability

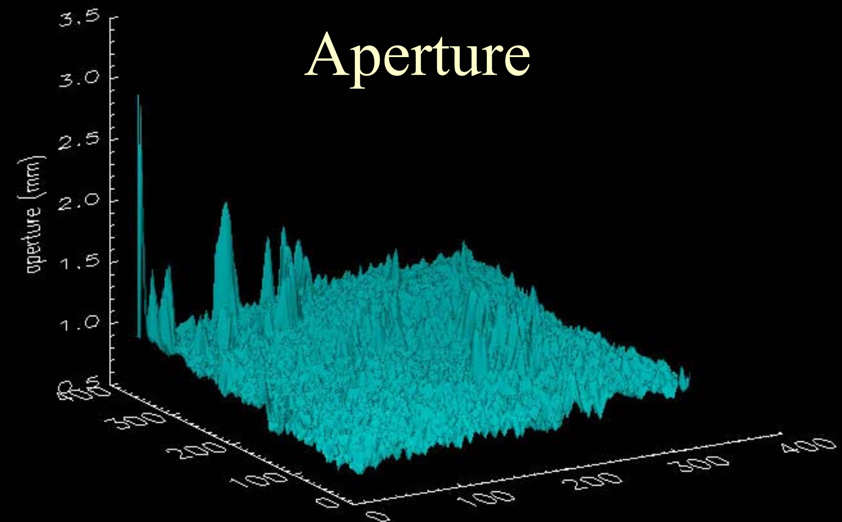
- Maps partial porosity on ~50 µm scale
- Also available:
  - Anisotropy
  - Orientation

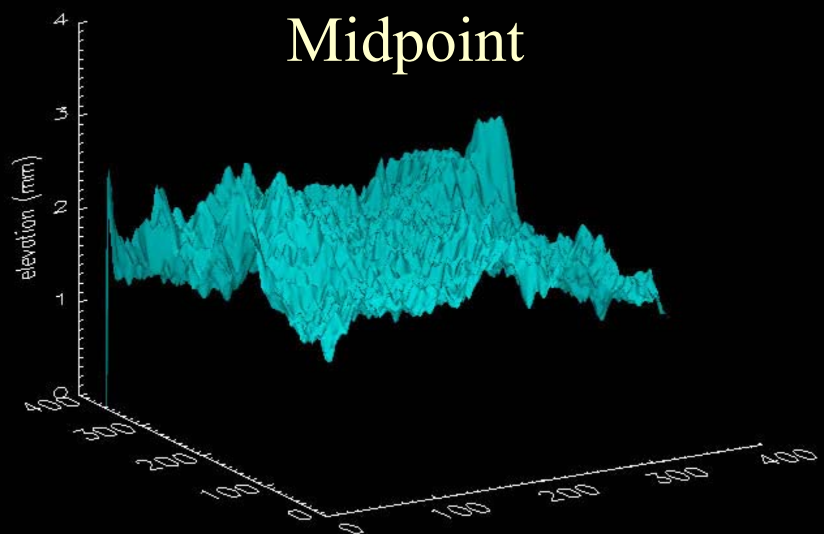


Fracture roughness



9 cm

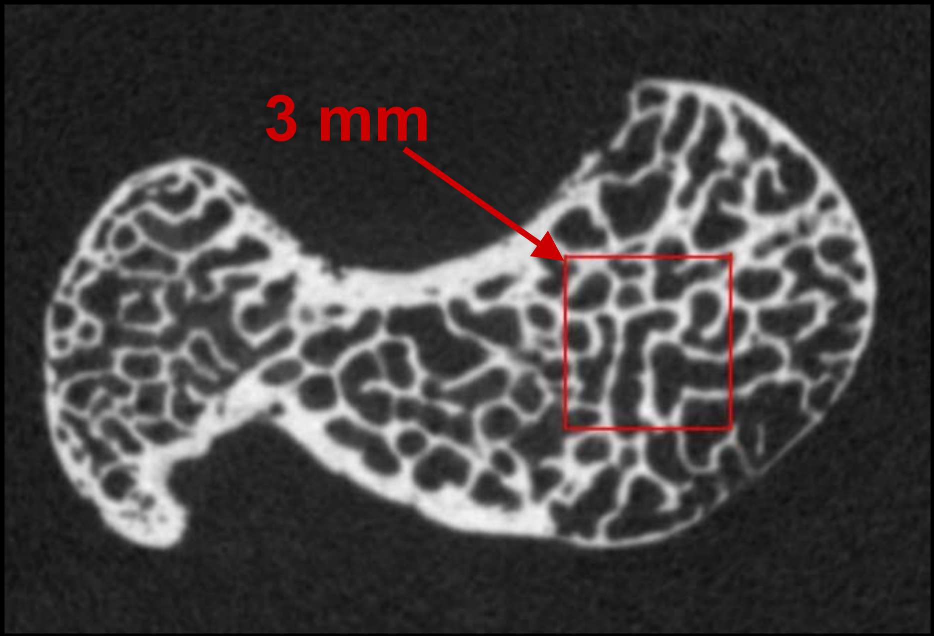


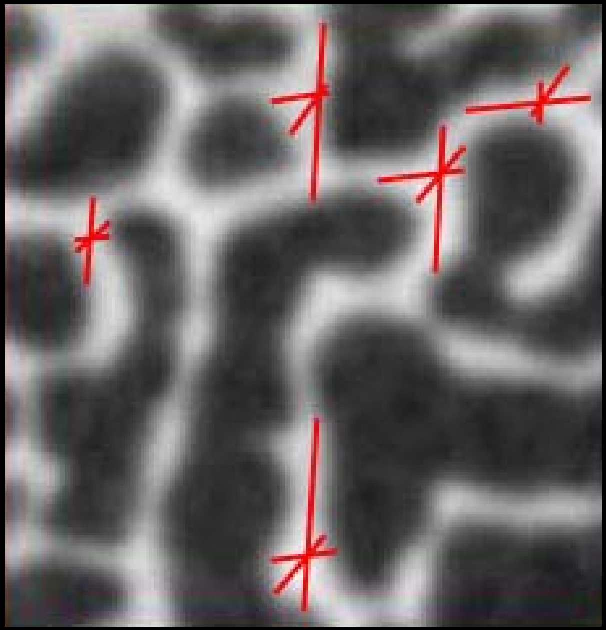


Project with Clark Thompson, UTDOGS

Structural Fabric

- Trabecular bone in primate limbs
  - Star Volume Distribution (SVD) analysis





Based on Ryan and Ketcham, 2002

Structural Fabric

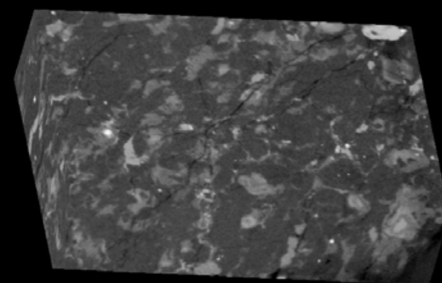
- Star Volume Distribution (SVD)
  - $V^*(\omega) = (\pi/3) \sum L^3(\omega)$
  - Star volume = Volume for convex solid
- Also Star Length Distribution (SLD)
  - $L^*(\omega) = \sum L(\omega)$

Structural Fabric

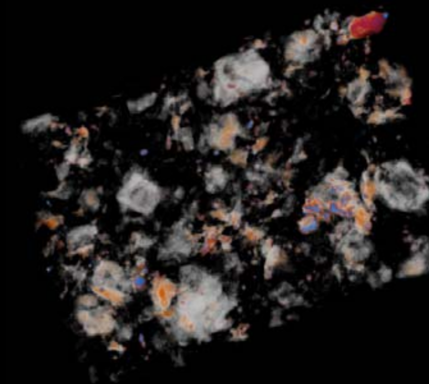
- Amount of data
  - ~512 directions, 8000 points
  - 4,000,000 measurements per determination!
- Compiled values define fabric tensors
  - Principal directions from eigenvectors
  - Anisotropy from eigenvalues

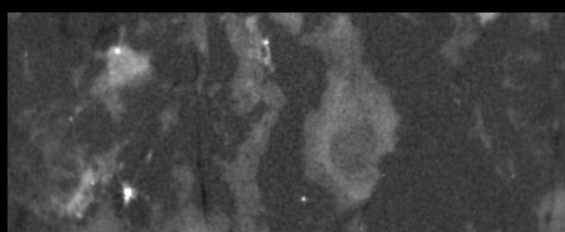
Mylonite development

C2-12, 3D reconstructions

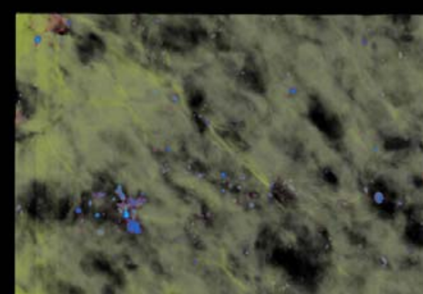


CT grayscales

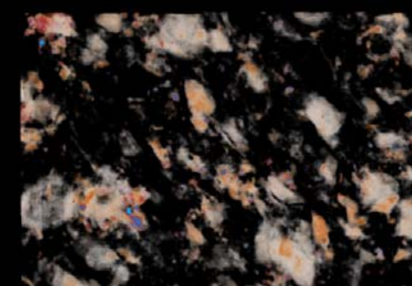




CT image



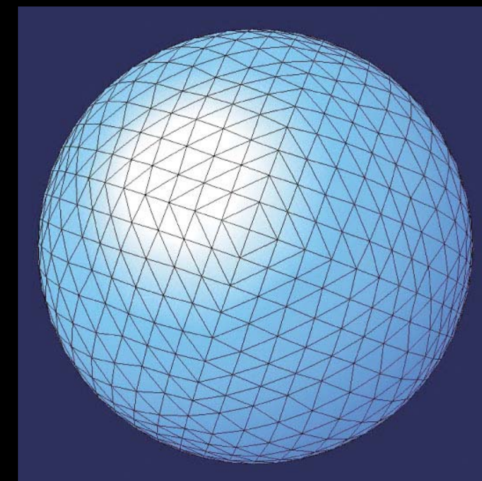
Quartz + Plagioclase

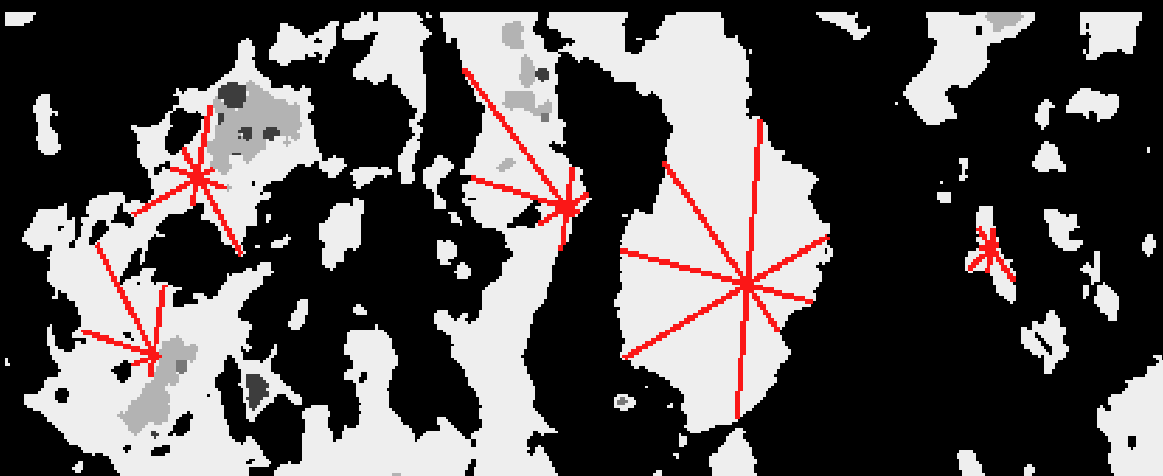


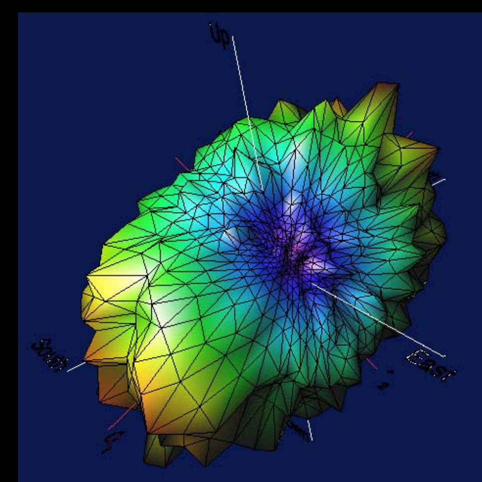
Orthoclase + Biotite

Gradational sequence from undeformed Wilderness Granite (Santa Catalina Mtns., AZ) to fully developed S-C mylonite.

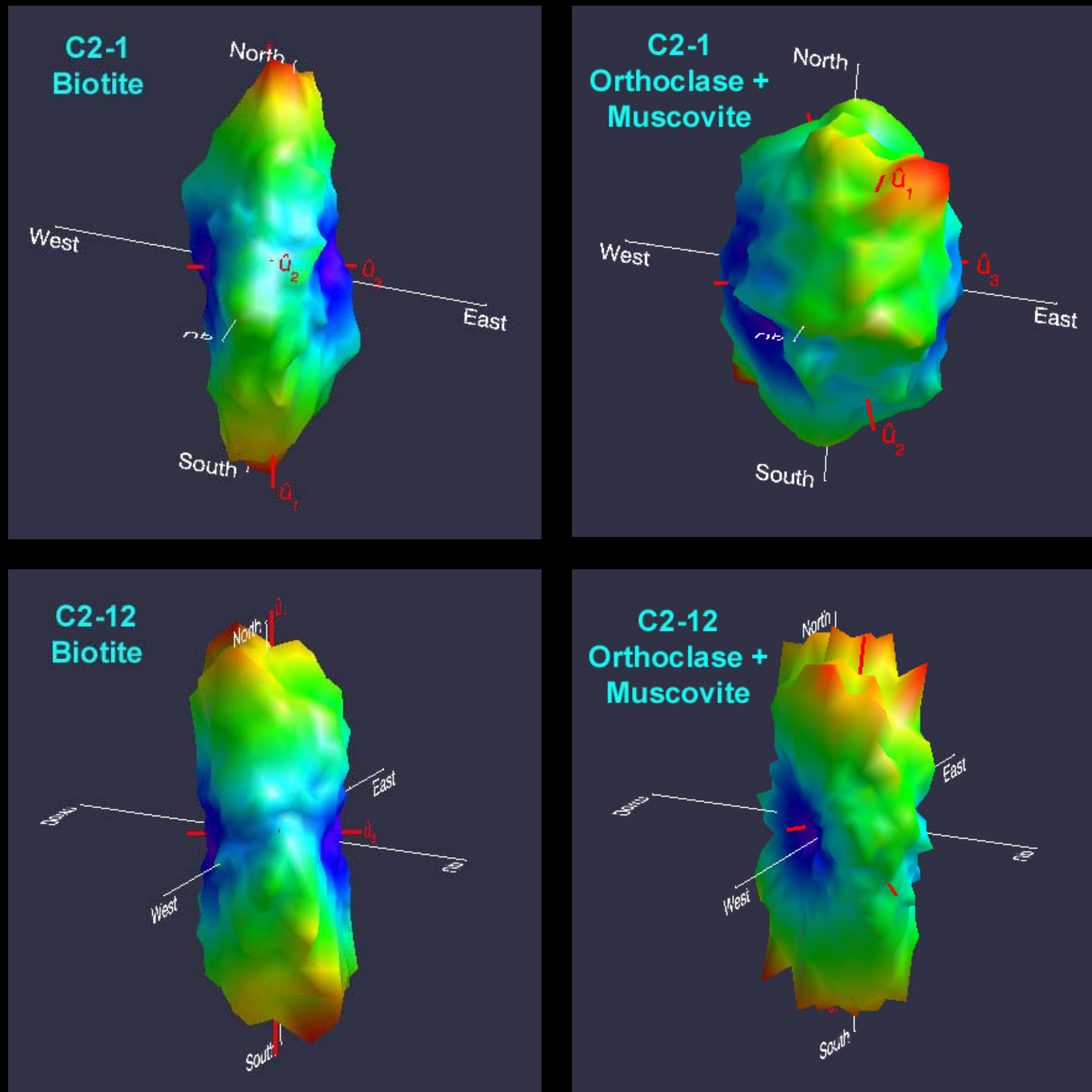
SVD calculation





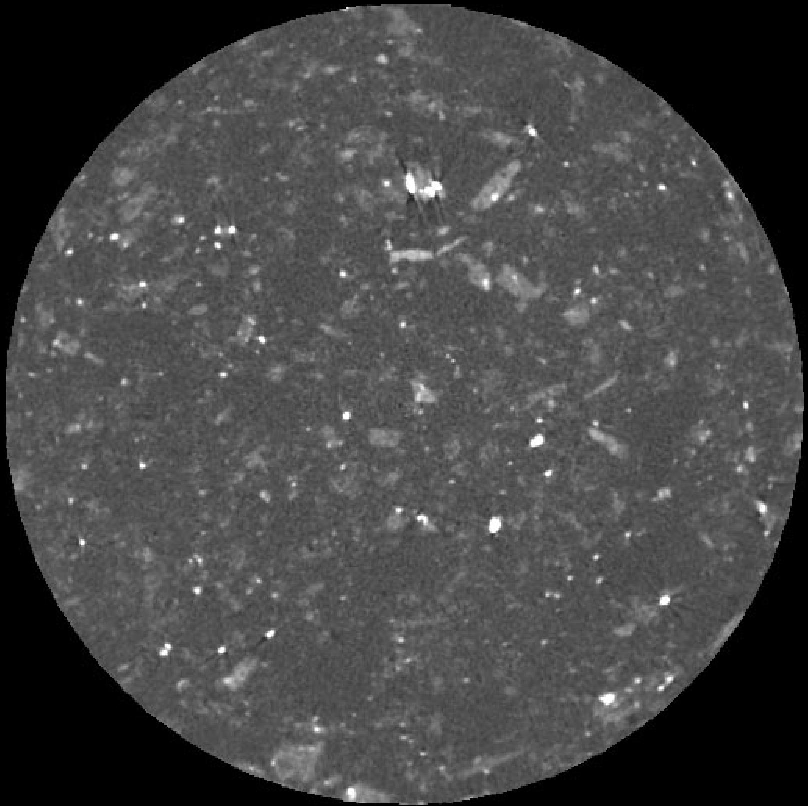


Foliation development

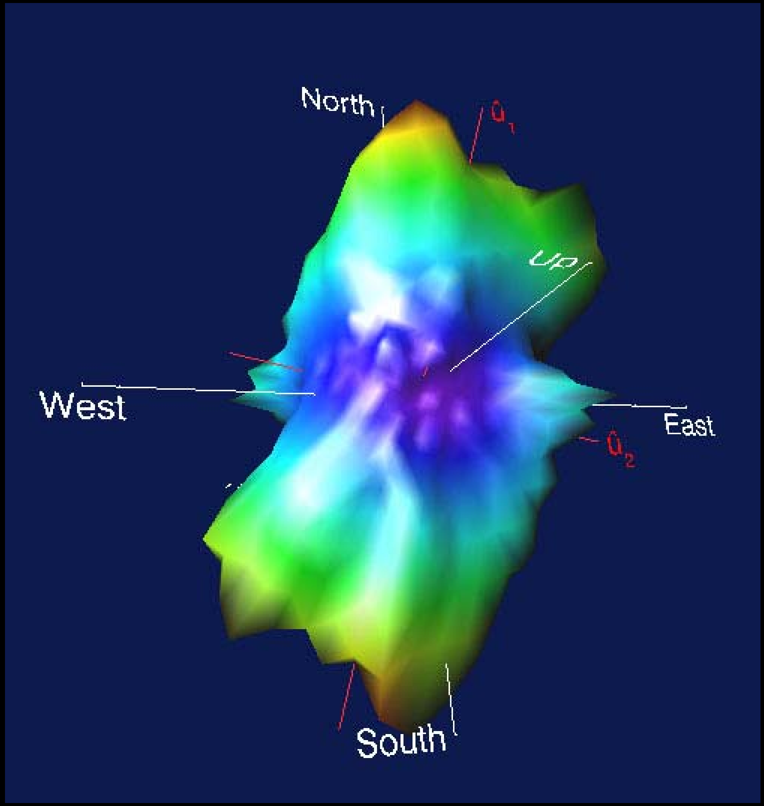


Phenocryst orientation vs. AMS

Foliated rhyolite
Henry Mountains, Utah
1” core



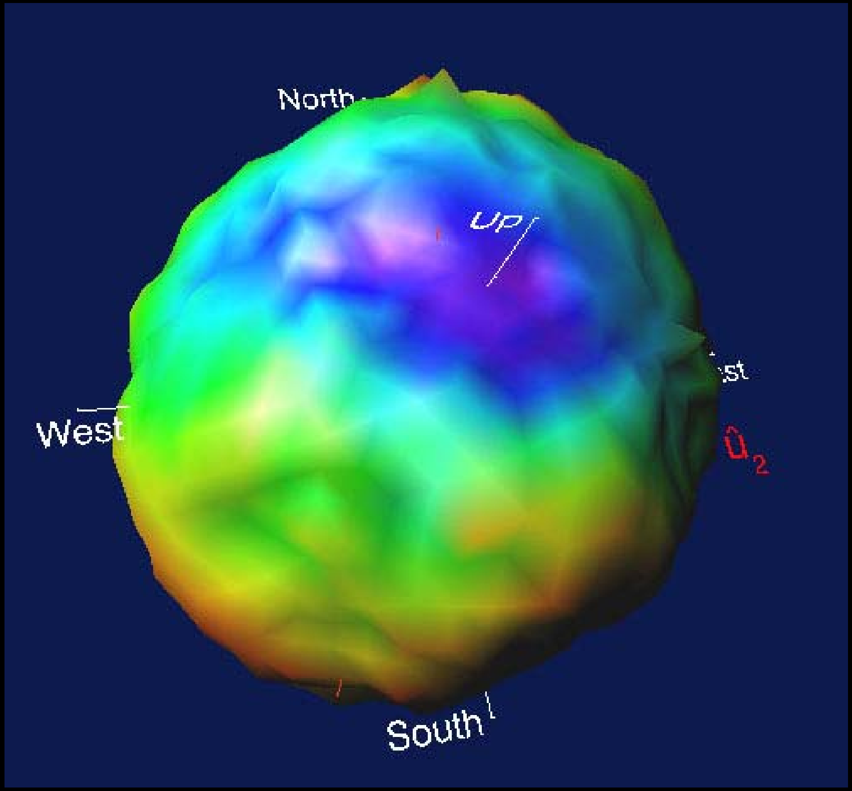
SVD, 3D rose
Amphibole orientations

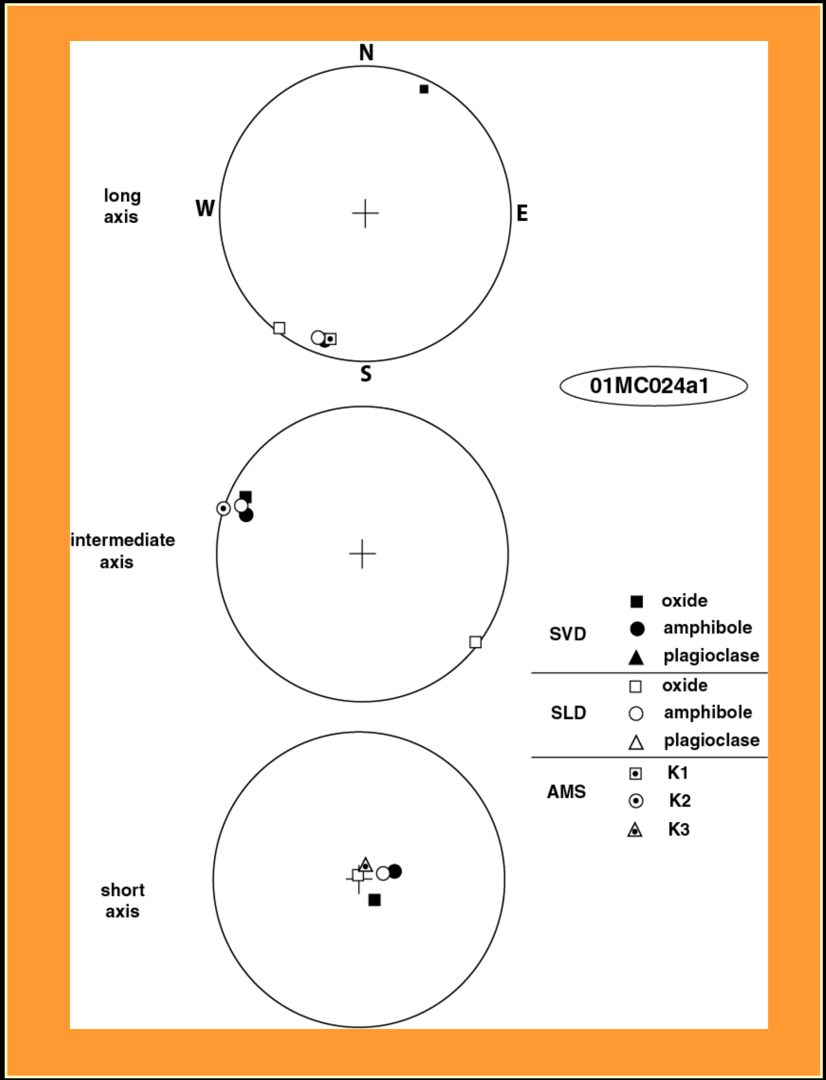


Study in collaboration with Eric Horsman and Basil Tikoff, U. Wisconsin

Phenocryst orientation vs. AMS

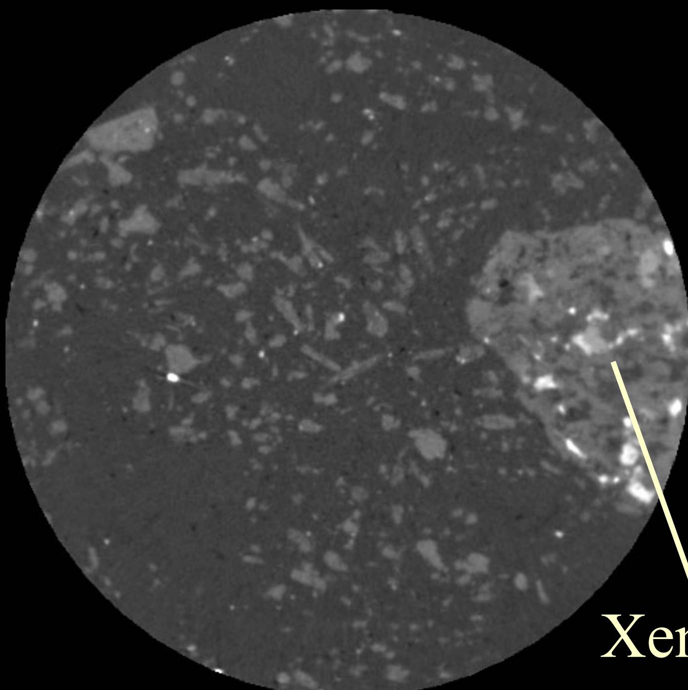
Oxides (magnetite)



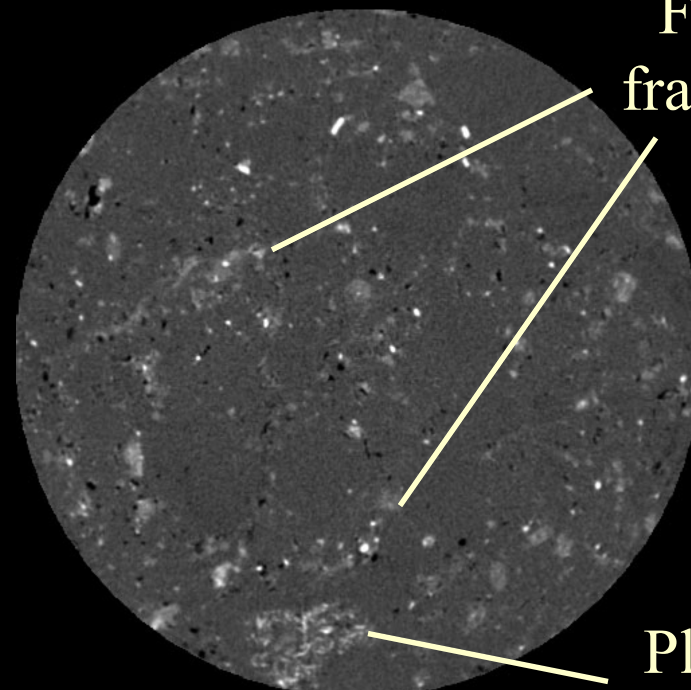


Phenocryst orientation vs. AMS

- Not all cases were as good…
  - But we can see some reasons why



200a



197b

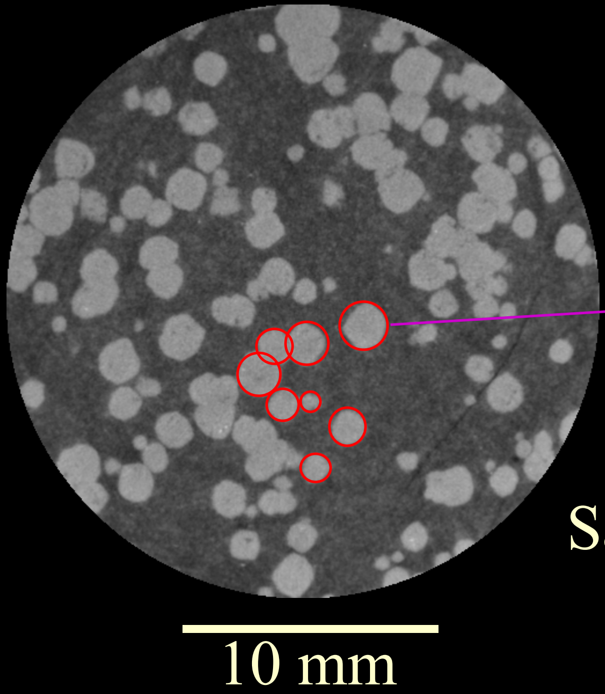
Object measurement

- Goal: Measure every "object" in a volume
  - Objects: porphyroblasts, vesicles, clasts, mineral grains, ???
  - Measurements: size, location, shape, orientation, center of nucleation, contact relationships, ???
- Some tricky parts
  - Objects might be touching or intergrown
  - There may be thousands of them

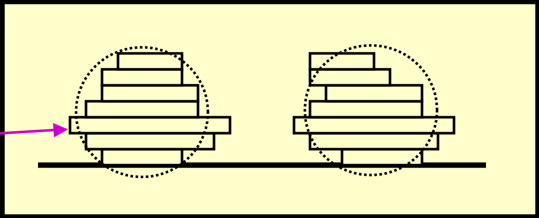
2D-based object measurement

1) Circles drawn over each garnet

2) Circles stacked to form spheres



Sample PM1

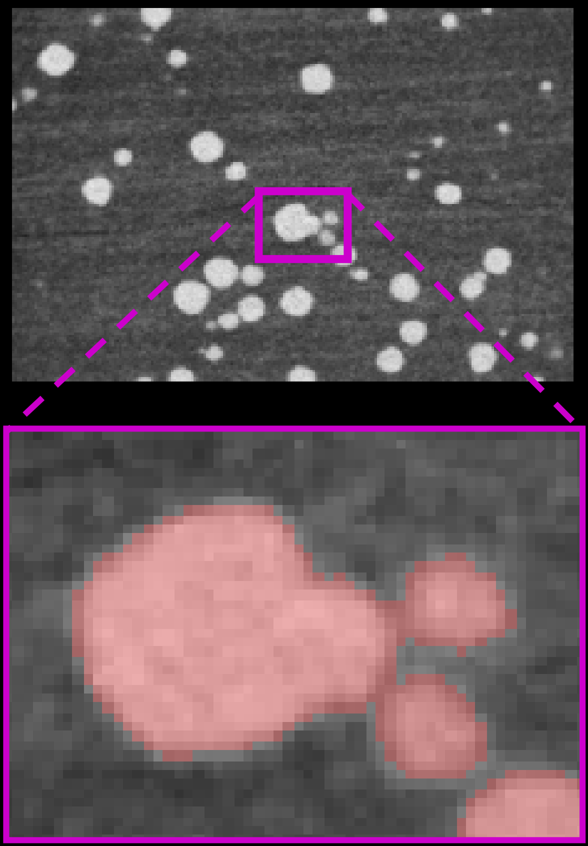


The BLOB3D Project

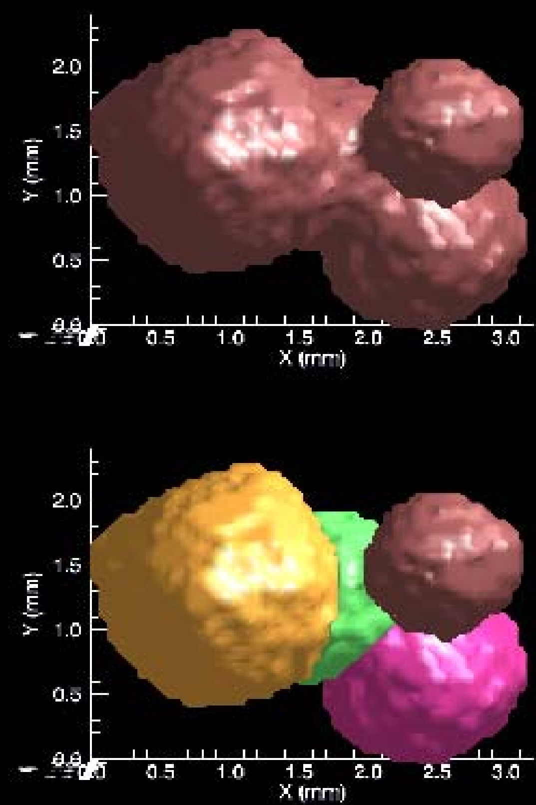
- 3D equivalent of 2D “blob” analysis
  - Blob: set of connected voxels
- Approach
  - User makes all choices
  - Object-oriented programming - expandable

Data processing in Blob3D

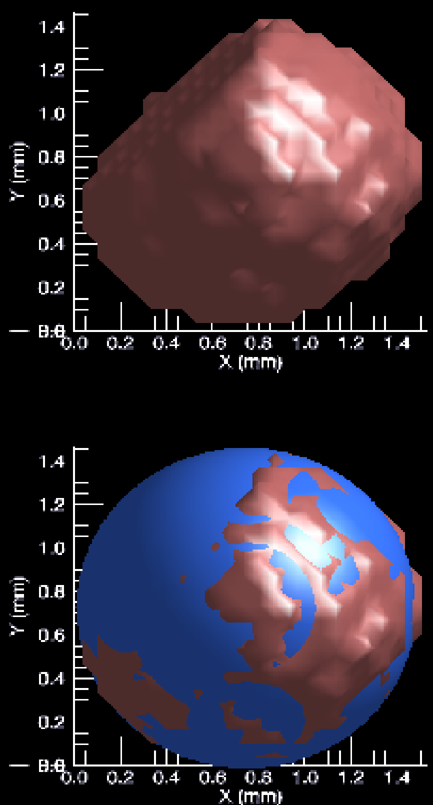
SEGMENT



SEPARATE



EXTRACT



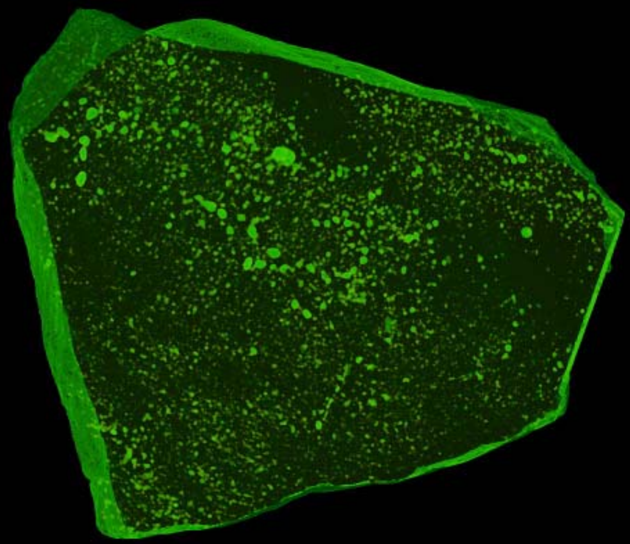
Cool example by Charna Meth

BLOB3D applications, so far

- Rich Kyle, Alison Mote, UT DOGS
  - Size distribution of Au grains
  - 2-phase fluid inclusion volumes
- Jeff Nettles and Hap McSween, U. Tenn.
  - "Aerodynamic stopping power" of troilite particles in meteorites
- Naga Shashidhar, Federal Highway Admin.
  - Asphalt concrete pavement evaluation
- Tim Rowe and Tom Eiting, UT DOGS
  - Nasal turbinates in skulls

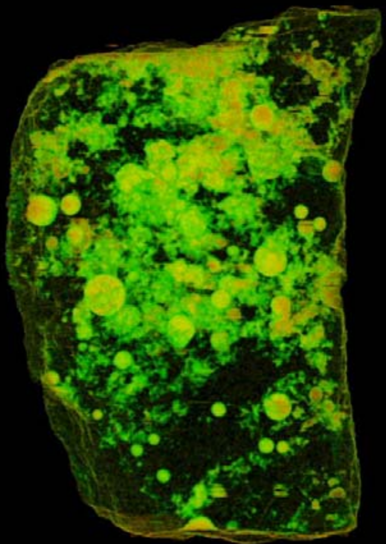
Vesicular basalt meteorites

Ibitira
eucrite



31,801 vesicles measured
Range: 0.003 – 14.1 mm^3
Median: 0.035 mm^3

D'Orbigny
angrite



101 vesicles measured
Range: 0.031 – 88.4 mm^3
Median: 2.61 mm^3

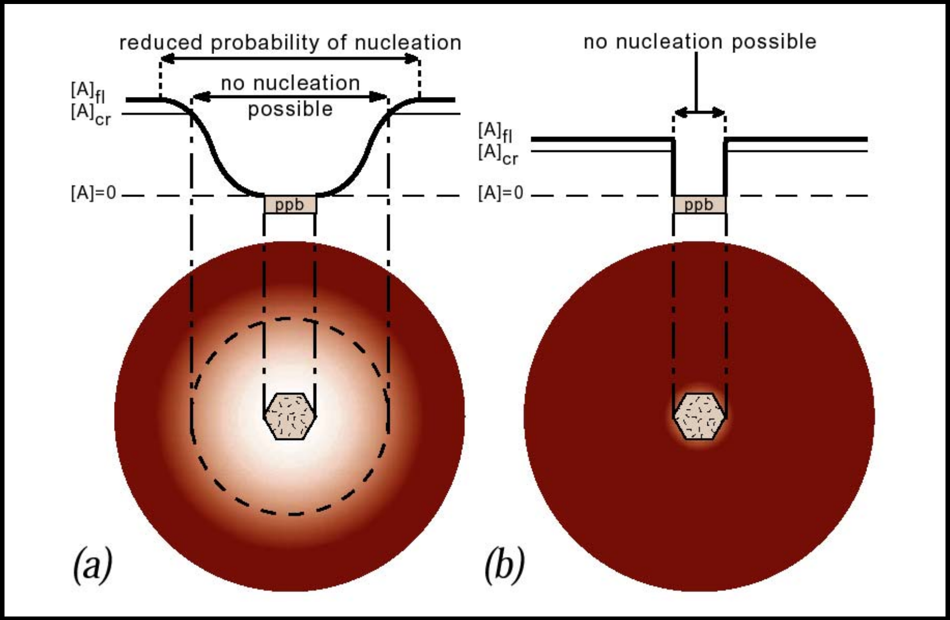
Project in collaboration with T. McCoy, G. Benedix, L. Wilson, W. Carlson

Vesicular basalt meteorites

- Some results:
  - D'Orbigny
    - Vesicle rise times very short: 43 seconds – 6 minutes
    - Must have essentially quenched at its liquidus
  - Ibitira
    - Layering implies dynamic system
    - Median vesicle rise time 50 hours
    - Implies minimum cooling rate of 1°C/hr
    - Vesicle nucleation began below 5 km chilled zone (4 Vesta)
    - Gas probably CO_2 rather than H_2O; ~50-200 ppm
    - Probably did not extrude at surface

Quantitative textural analysis

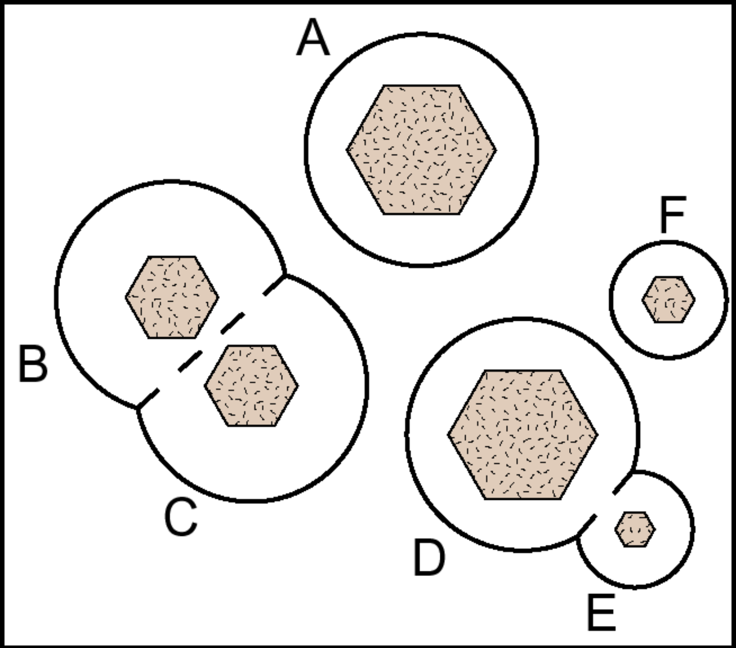
- The Problem: What is the rate-limiting process in (metamorphic) crystal growth?
  - Intergranular diffusion or interface reaction?
- The Idea: Diffusion may influence texture



From Hirsch et al., 2000

Quantitative textural analysis

- The Problem: What is the rate-limiting process in (metamorphic) crystal growth?
  - Intergranular diffusion or interface reaction?
- The Idea: Diffusion may influence texture

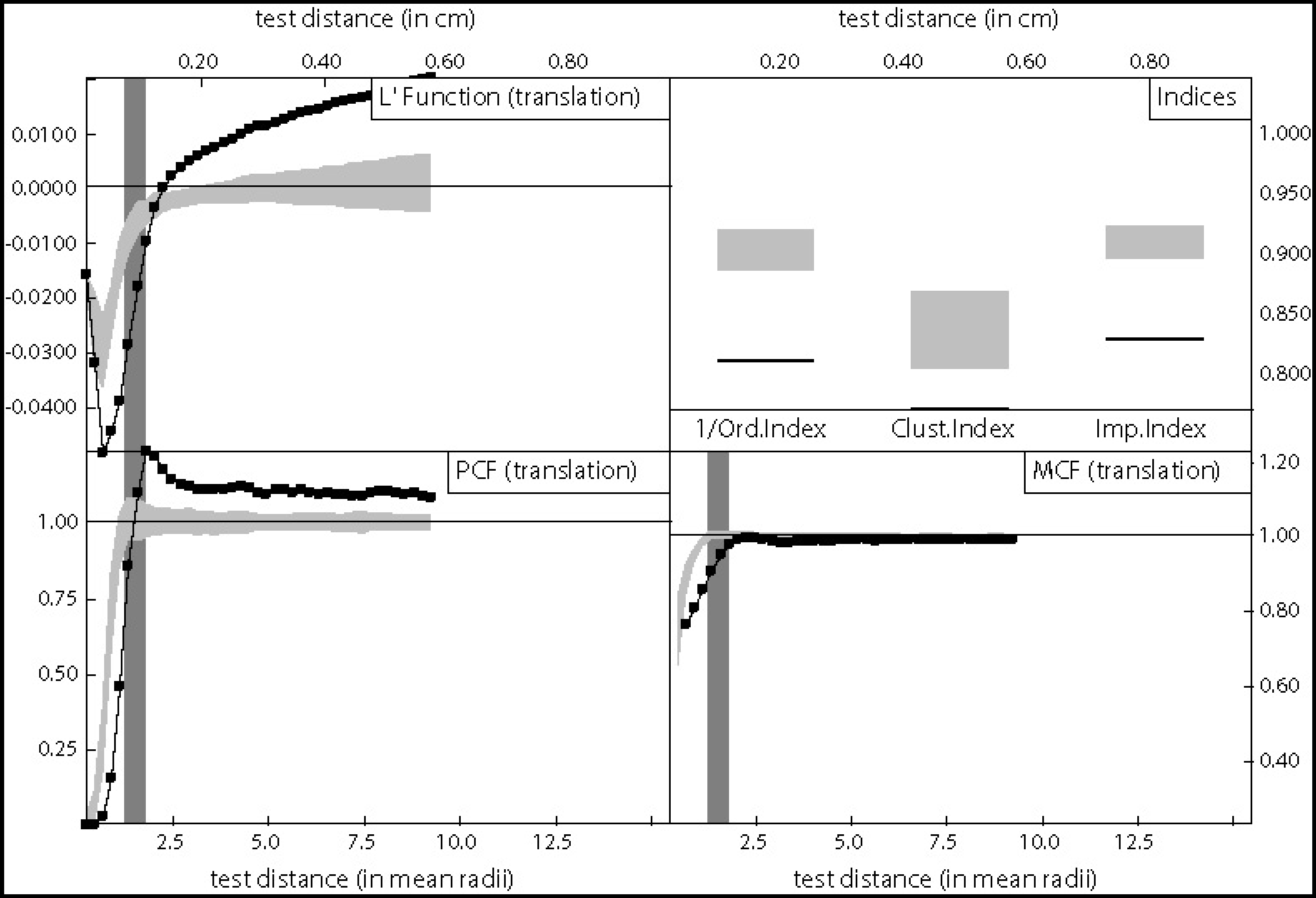


After Carlson, 1989

Detecting ordering, clustering

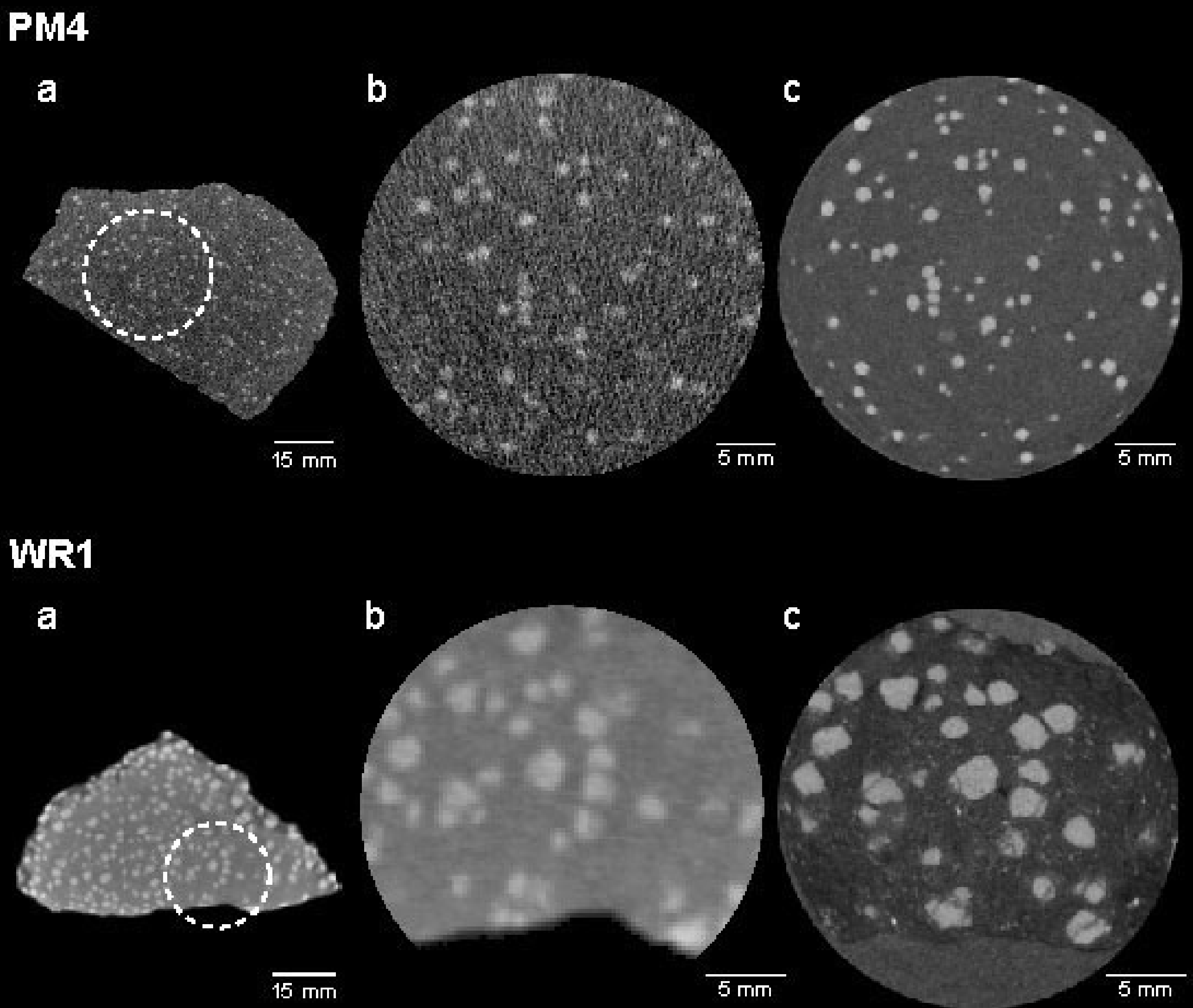
- Single-valued statistics (Carlson and Denison, 1992; Denison et al., 1997)
  - Ordering Index (OI), Clustering Index (CI), Impingement Index (II)
- Correlation functions (Raeburn, 1996; Hirsch et al., 2000)
  - Inspects range of length scales, compares to semi-random case
  - PCF: Crystal centers
  - MCF: Crystal volumes

Old data, PM1



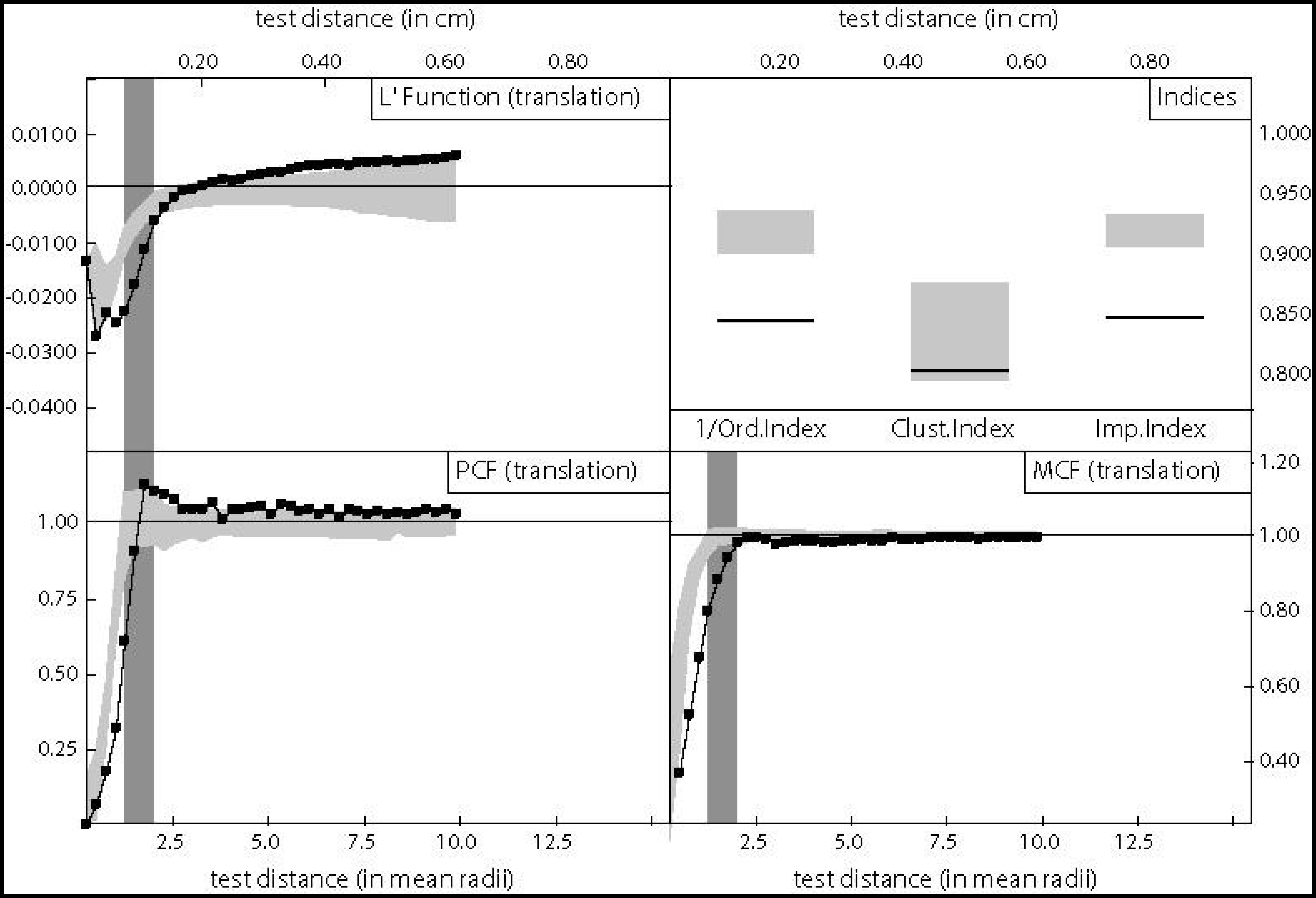
test distance (in cm)
0.20
0.40
0.60
0.80
L' Function (translation)
0.0100
0.0000
-0.0100
-0.0200
-0.0300
-0.0400
test distance (in cm)
0.20
0.40
0.60
0.80
Indices
1.000
0.950
0.900
0.850
0.800
1/Ord.Index
Clust.Index
Imp.Index
PCF (translation)
1.00
0.75
0.50
0.25
MCF (translation)
1.20
1.00
0.80
0.60
0.40
2.5
5.0
7.5
10.0
12.5
test distance (in mean radii)
2.5
5.0
7.5
10.0
12.5
test distance (in mean radii)

Old vs. new CT imagery

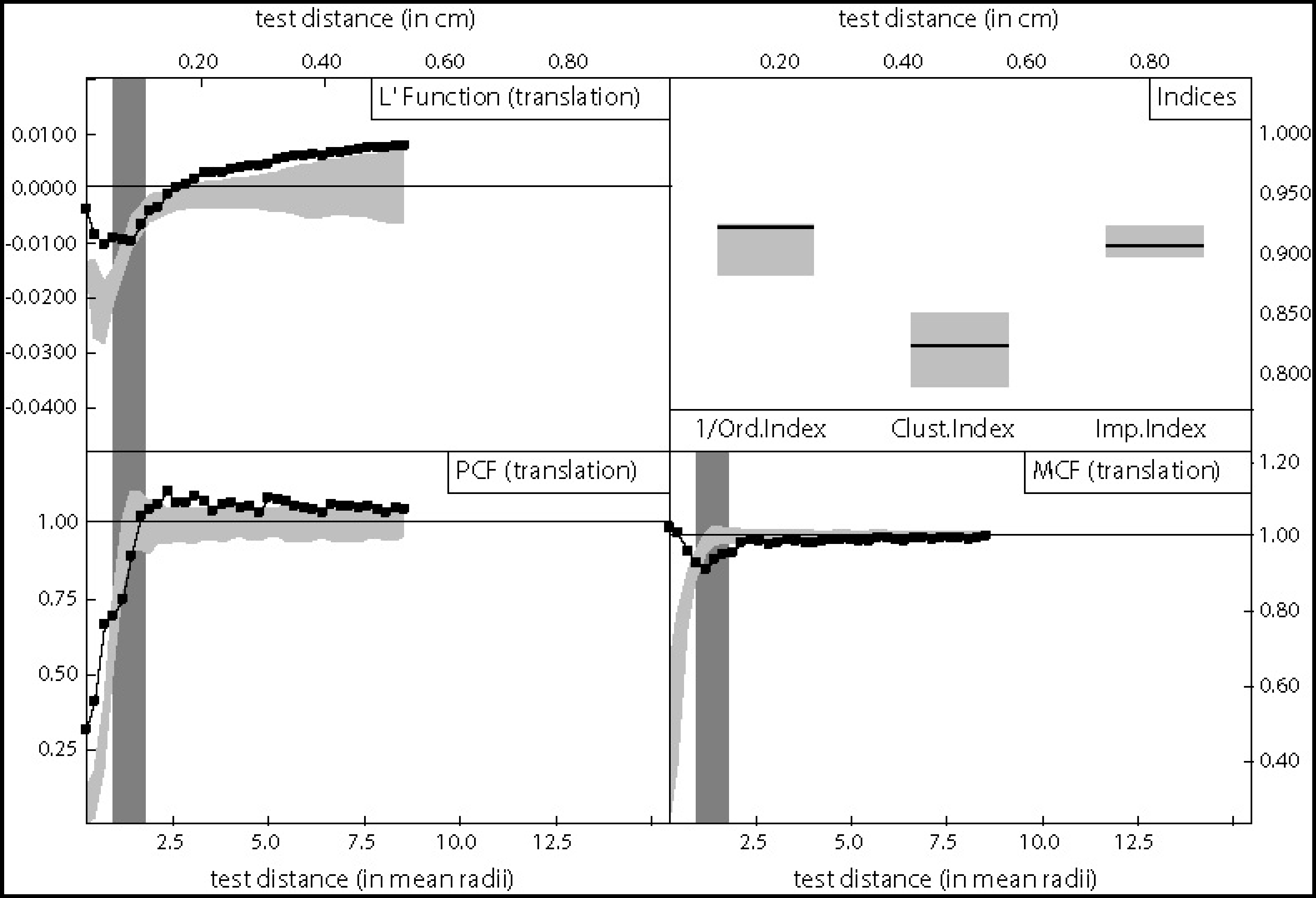


Cool example by Charna Meth

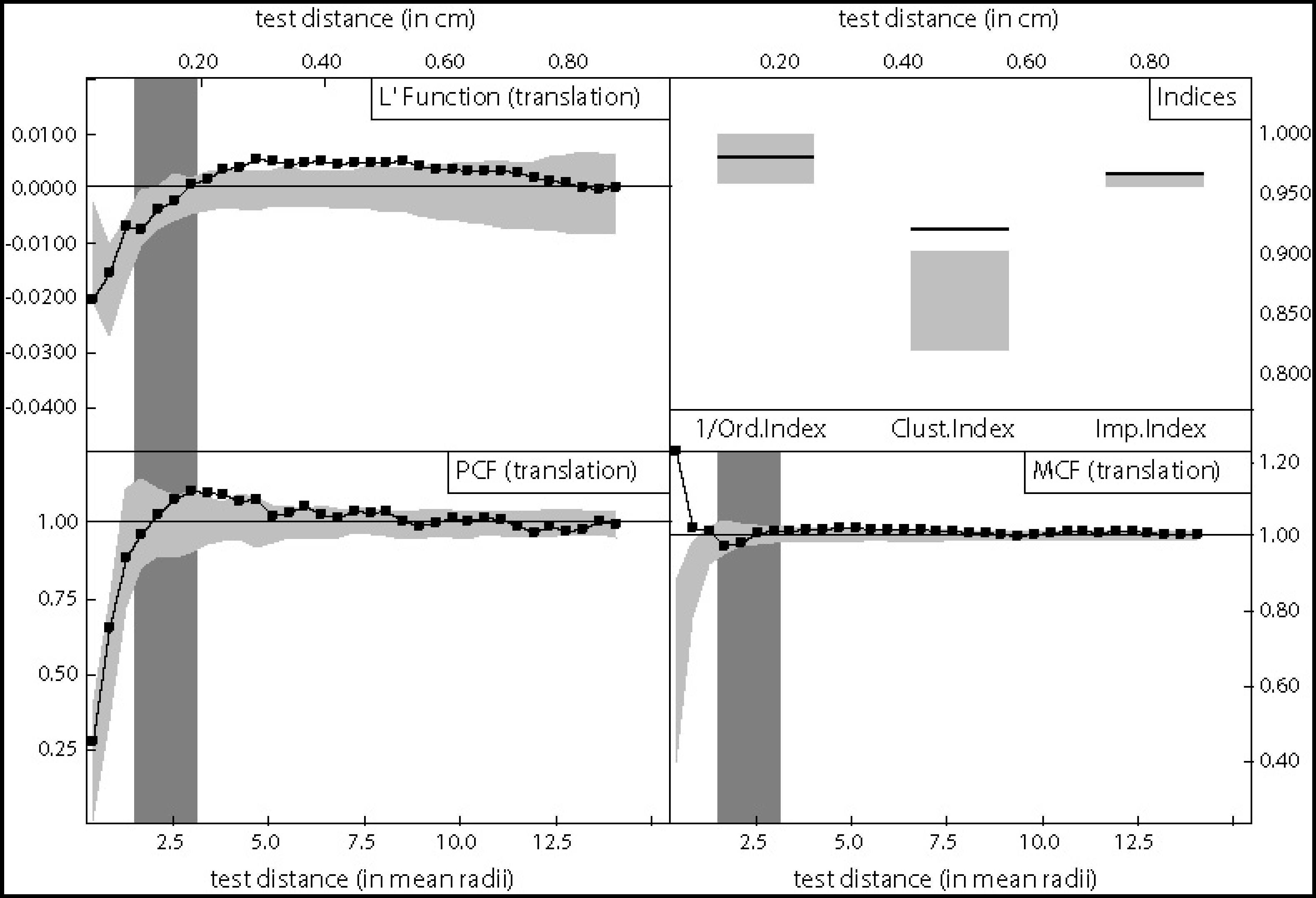
New data, PM1, no primitive fitting



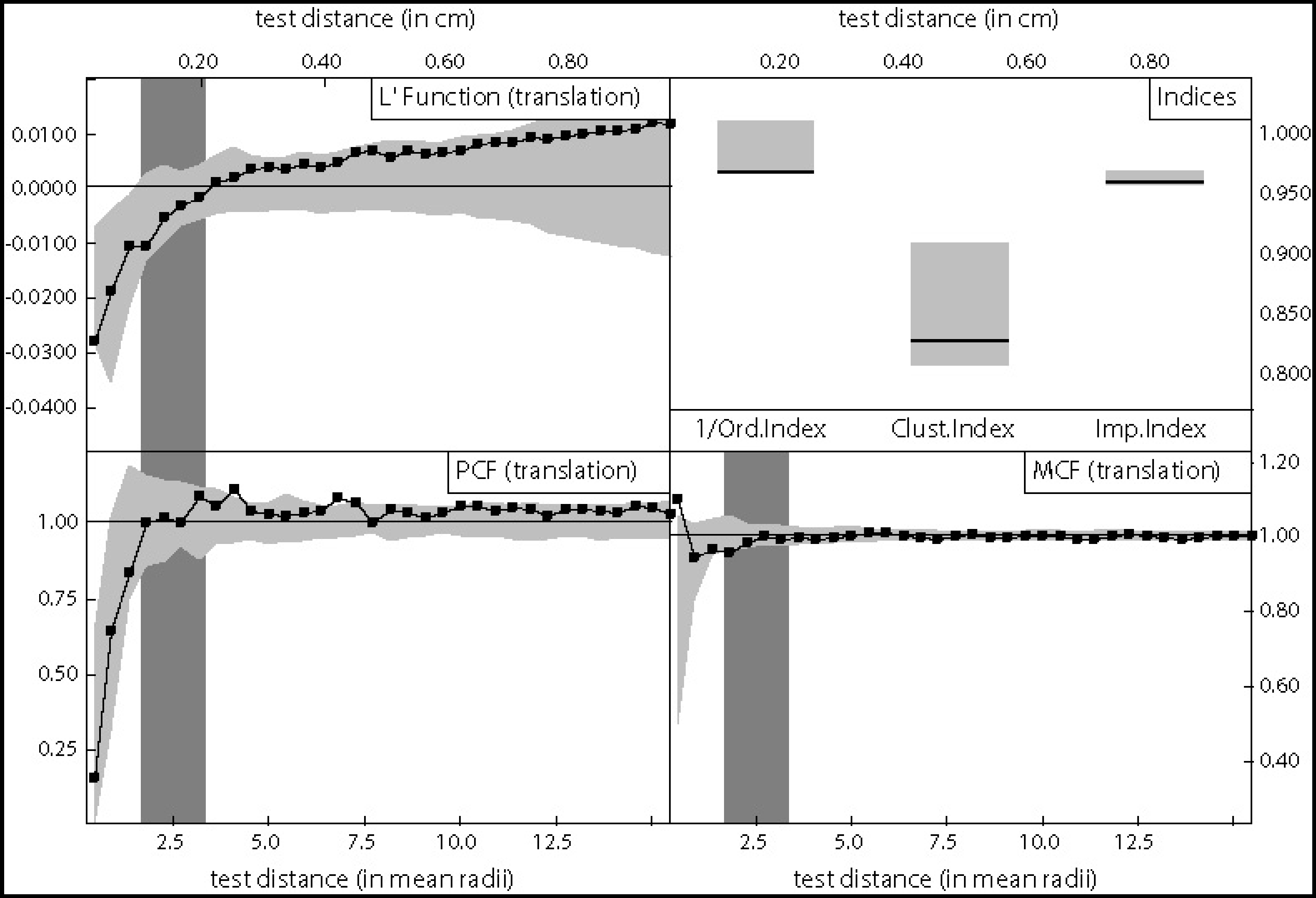
New data, PM1, primitive fitting



New data, PM2, primitive fitting



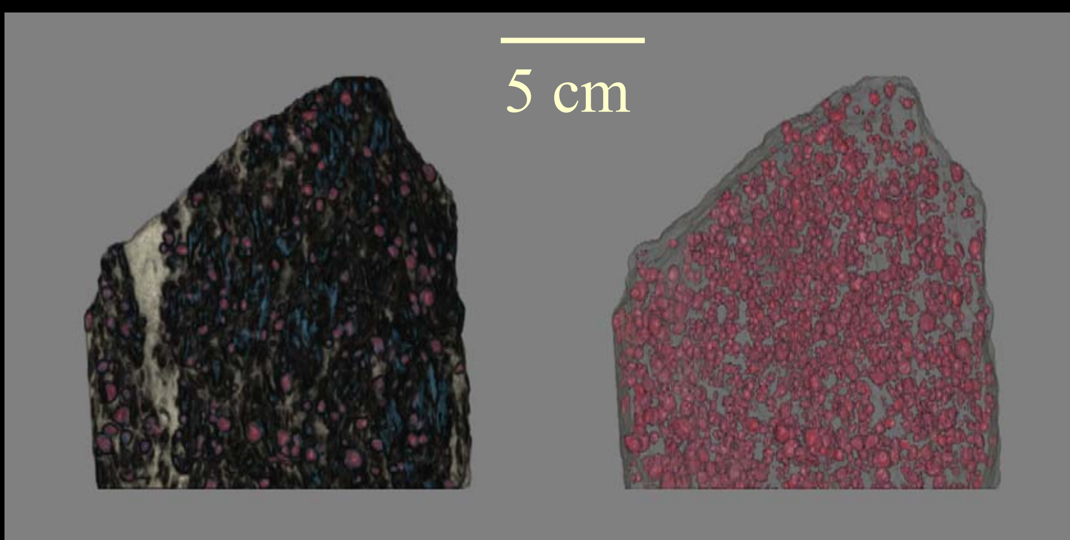
New data, PM4, primitive fitting

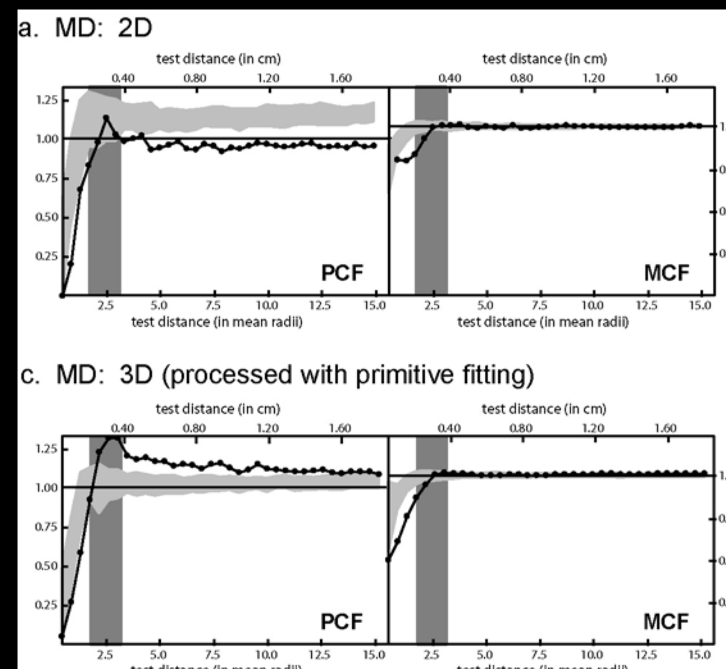


More old and new

Garnet-kyanite schist, Mica Dam, British Columbia (Sample MD, Carlson and Denison, 1992; Denison and Carlson, 1997)

Whole sample Garnets only

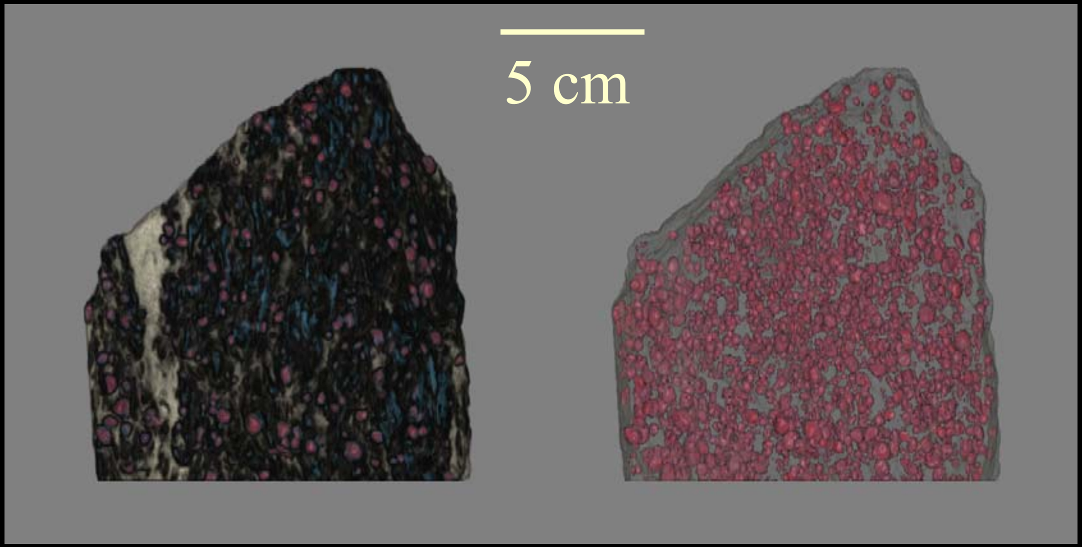




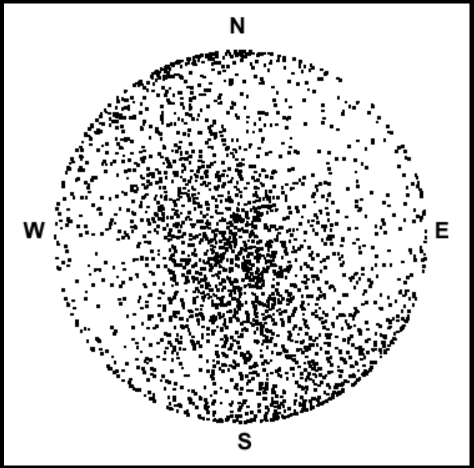
New data, MD

Garnet-kyanite schist, Mica Dam, British Columbia (Sample MD, Carlson and Denison, 1992; Denison and Carlson, 1997)

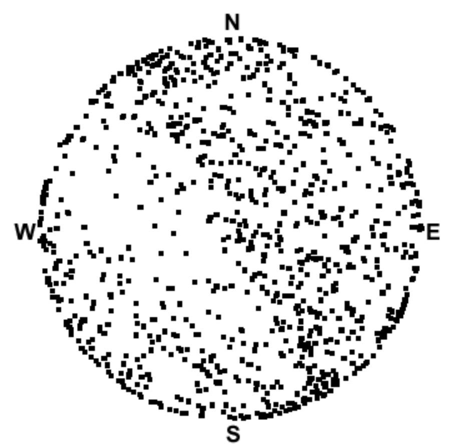
Whole sample   Garnets only



Garnet long axes



Garnet-garnet contacts

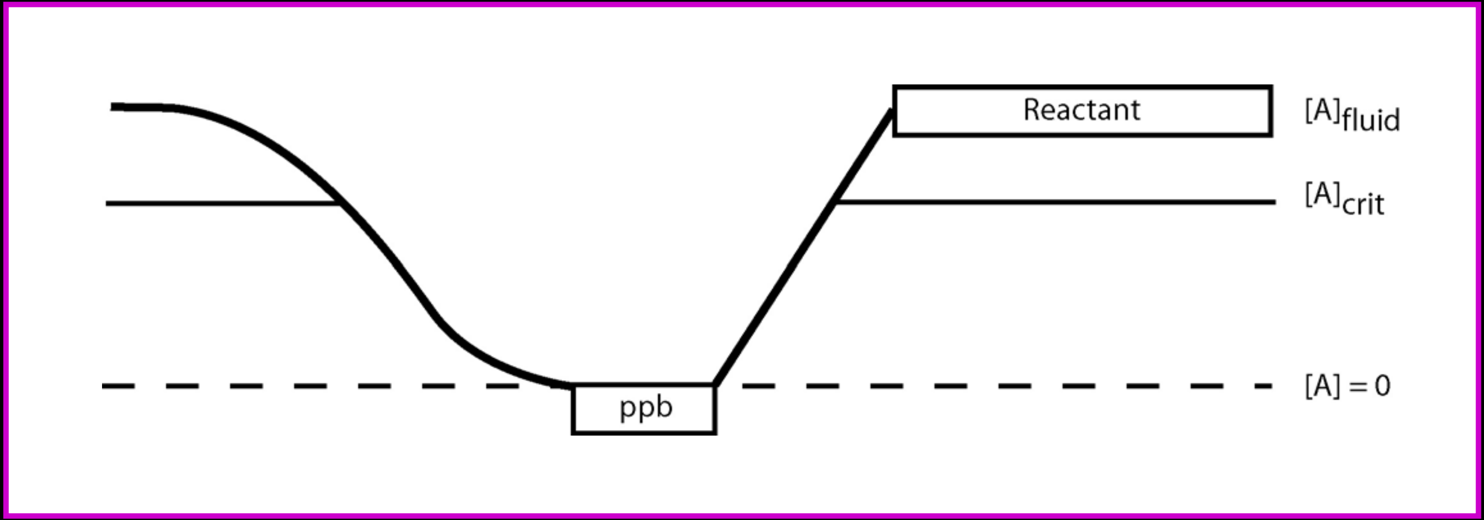


What's this mean?

- Old data likely inadequate for detecting and measuring impingement
- There is no textural evidence for ordering in Picuris samples
  - Perhaps some signal for competition
- BUT there *is* chemical evidence for diffusion control (Carlson, 1989)

Some ideas

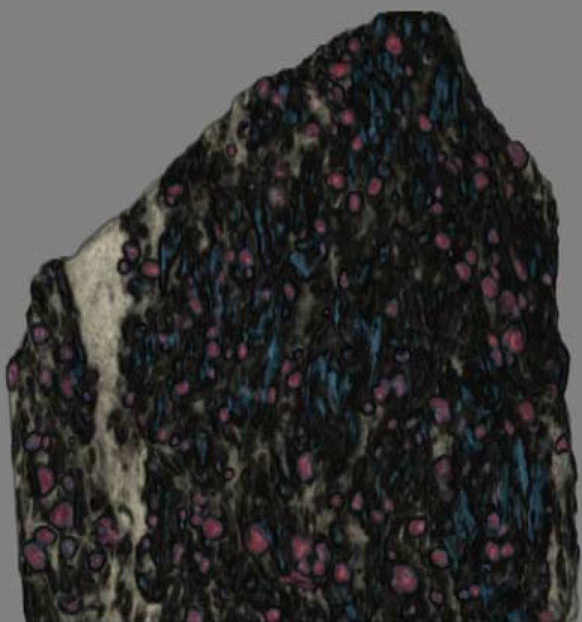
- Dissolution rates also partly controlled by diffusion.
- "Dissolution front" may inhibit ordering but allow competition.



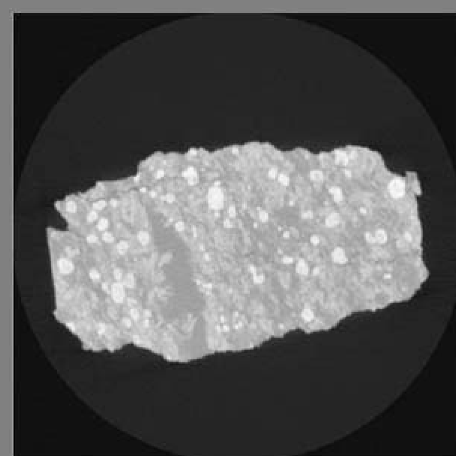
The End

Garnet-kyanite schist from Mica Dam, British Columbia

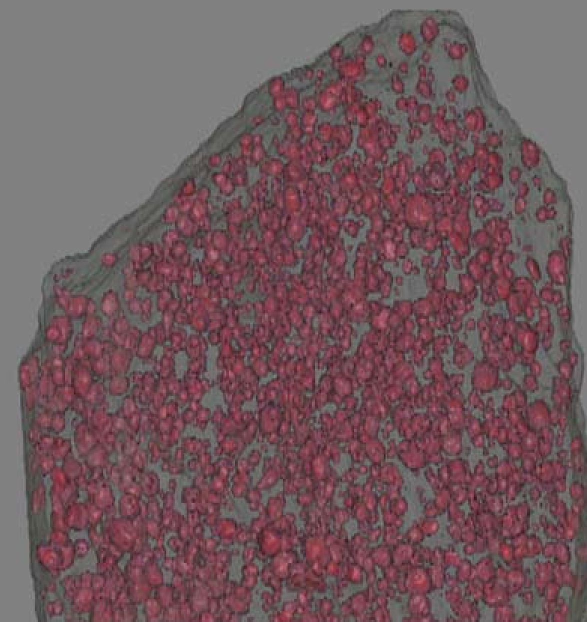
Objective: Determine size, shape and location of garnets;
Compare to tectonic fabric



3D reconstruction



Original scan data
(FOV = 128 mm)



3D recon, garnets only